SELF-ASSEMBLED MONOLAYER FILMS AS DURABLE ANTI-STICTION COATINGS FOR POLYSILICON MICROSTRUCTURES

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ABSTRACT

We present a self-assembled monolayer (SAM) coating process for high-yield release of compliant polysilicon microstructures – direct from the water rinse. This process has been used to release cantilever beams up to 1000 microns in length and requires no special sublimation or supercritical drying techniques. Once coated and released, these same microstructures have been used to quantify in-use stiction by electrostatically actuating surfaces into contact. Polysilicon structures coated with SAM films exhibit a work of adhesion of $3 \mu\text{J}/\text{m}^2$, nearly four orders of magnitude lower than uncoated, hydrophilic structures. These coatings are also thermally stable up to 400°C for 5 minutes in a nitrogen or vacuum ambient, which falls within the range of typical packaging temperature cycles. The SAM-coating process has been further improved to eliminate the use of carbon tetrachloride, an environmentally unfriendly solvent. Using a combination of chloroform and iso-octane in place of the carbon tetrachloride, films have been produced which exhibit equal or better stiction properties than those formed using the carbon tetrachloride process.

INTRODUCTION

Despite years of advancement in bulk and surface micro-machining technologies, stiction of microstructures remains a fundamental problem. Stiction most often manifests itself during the structure release process, where liquid capillary forces deflect compliant structures into contact with adjacent surfaces. Subsequent evaporative drying leads to solid bridging due to precipitates left behind from the liquid phase, which usually results in permanent sticking at this stage [1-3]. This *release-related stiction* has been successfully evaded by several methods, including sublimation drying [1,4], supercritical drying [5], and dry-release [6,7] techniques that avoid the formation of a liquid-vapor interface altogether. In addition, small features have been added to the microstructure perimeter to reduce capillary forces by shaping the liquid meniscus [8].

The second manifestation of stiction is during actual device operation, termed *in-use stiction*. When adjacent microstructure surfaces come into contact (intentionally or unintentionally), capillary, electrostatic, and van der Waals forces may all contribute to adhesion of the surfaces and device failure [2]. None of the techniques mentioned above for the alleviation of release stiction addresses the problem of in-use stiction, which is becoming more important as increasingly compliant microstructures and vacuum packaging are introduced [9,10]. Initial attempts to alleviate in-use stiction focused on reducing the contact area between adjacent surfaces by fabricating micro-dimples [11,12] or by roughening the polysilicon surface on a more microscopic level [13,14]. While some improvements (factor

of ~5) were seen due to roughening, attention has turned more recently towards chemical passivation of the polysilicon surface.

One approach to surface passivation introduced self-assembled monolayers (SAMs) into microfabricated devices. Alley *et al.* showed promising results for alleviating release-related stiction and suggested SAMs as a potential post-release anti-stiction lubricant [2]. However, due to the stiffness of the structures investigated, no quantitative measure of the stiction properties of SAM-coated surfaces could be made at that time. Further work involving SAM films by Deng *et al.* showed a marked improvement in the release and wear properties of SAM-coated polysilicon wobble motors. Motors with a SAM coating operated for nearly 80 million cycles over a nine month period, indicating low wear and good durability of these films even on surfaces in continuous moving contact [15].

More recently, a method for measuring the work of adhesion between contacting surfaces using cantilever beam arrays showed that hydrogen passivation of the polysilicon surface reduced in-use stiction by over three orders of magnitude [16]. This technique made use of an ammonium fluoride treatment coupled with supercritical drying to release microstructures with a hydrogen-passivated polysilicon surface. One drawback to this approach, however, was the metastable nature of the hydrogen-terminated silicon surface which limited the long-term usefulness of such a treatment [17]. Hydrogen-terminated silicon surfaces are likely to be further degraded by packaging processes which typically require temperatures of $300\text{--}425^\circ\text{C}$, a stringent requirement for surface passivation coatings. In another approach recently introduced, fluorocarbon films formed by a plasma polymerization reaction have shown success in reducing post-release adhesion [18].

A low-stiction, chemically-stable surface coating capable of surviving packaging temperature cycles is highly desirable. This work demonstrates that the SAM coating process previously studied by Alley and Deng is effective at reducing both release and in-use stiction. The SAM film is comprised of a close-packed array of alkyl chains which spontaneously form on oxidized silicon surfaces, and have been shown to remain stable indefinitely (up to 18 months in air to date) in numerous environments [19]. The extremely hydrophobic nature of SAM-coated surfaces changes the meniscus shape such that microstructures are not collapsed by capillary forces. As a result, extremely compliant structures may be pulled directly out of water, from which they emerge released and completely dry without post-processing. Furthermore, these films reduce in-use stiction by several orders of magnitude, and their thermal stability is sufficient to withstand various packaging processes. A description of the formation/release process, thermal stability, and in-use stiction properties of SAM-coated polysilicon microstructures will be presented in the following sections.

BASICS OF SAM FORMATION

The films studied in this work were formed from octadecyltrichlorosilane (OTS) precursor molecules having a chemical formula of $C_{18}H_{37}SiCl_3$. When the precursor molecules are placed into a suitable solvent such as a 4:1 hexadecane:carbon tetrachloride (CCl_4) mixture and an oxidized silicon surface is inserted, the trichlorosilane head groups hydrolyze and chemisorb to the surface, forming Si-O-Si links to the surface [20]. The process showing assembly of the film is depicted schematically in Fig. 1. After formation, the film is further stabilized by cross-linking between chains, a process often aided by a low temperature anneal after film formation ($\sim 100^\circ\text{C}$). When prepared correctly, a SAM-coated Si(100) oxide surface (prepared using OTS) exhibits a water contact angle of $114^\circ \pm 2^\circ$, which corresponds to a surface energy of about 20 mJ/m^2 . The film thickness is about $25\text{ \AA}$, and the film "density" is approximately 5 chains per nm^2 ($\sim 90\%$ of the density of crystalline polyethylene), indicative of a true "monolayer" coverage [21].

Figure 1. Schematic of self-assembled monolayer formation on an oxidized silicon surface using alkyl-trichlorosilane precursor molecules. Film formation is thought to occur within several minutes on smooth surfaces.

There are two particularly important factors involved in obtaining high-quality SAM films [21]. First, the presence of water in the SAM solution is undesirable because water will cause conglomeration of the OTS precursor molecules. Water is thought to be *necessary*, however, in the form of a thin film on the silicon dioxide surface. This water is responsible for hydrolyzing the trichlorosilane head groups and may promote mobility of the SAM chains, allowing them to move into close-packed structures. Thus, while bulk water must be washed away before placing samples into the SAM solution, hydrophilic silicon surfaces which retain a thin layer of water molecules are desirable for high-quality SAM films formed from these precursor species.

The second important factor in obtaining high-quality films is the temperature at which the films are formed. Specifically, a transition temperature has been observed near room temperature, below which the SAM films display superior properties [22]. In

general, this transition temperature drops as the tail chain length becomes shorter. For OTS, the transition temperature is reported to be approximately 28°C . The existence of such a transition temperature also appears to have important ramifications for forming SAM films from other precursor species, such as fluorinated trichlorosilanes (FTS) [22]. This may be one explanation for the poor performance seen in FTS films studied thus far for micromachining anti-stiction applications [2,15].

One remarkable property of these films is their stability after formation [19]. Specifically, storage times of up to 18 months in air produced indistinguishable thicknesses and contact angles from freshly prepared films. Furthermore, SAM films appear to be impervious to hot organic solvents, acidic media, and boiling water. Even rubbing of the surface with a tissue produced no detectable changes in the film properties, further evidence of film durability. The long-term stability of these film in various ambients, coupled with their low surface-energy, hydrophobic, densely-packed structure, makes self-assembled monolayers an exciting option for anti-stiction coatings in micromachines.

EXPERIMENTAL PROCEDURES

The structures used to characterize the release and in-use stiction properties of the SAM coatings in this work consisted of arrays of $10\text{ }\mu\text{m}$ -wide cantilever beams, which extended from 50 to 1000 microns in length. Between 50 and 260 microns, the beams were incremented in 10 micron lengths; the longer beams were incremented by 20 microns. These structures were fabricated using standard surface micromachining techniques. After thermal oxide growth and low-stress nitride deposition, a $3000\text{ \AA}$ in-situ doped polysilicon film was deposited and patterned as the ground-plane layer. The deposition conditions were 590°C , 500 mtorr , PH_3 mole fraction = 3.2×10^{-3} , balance SiH_4 . A $2\text{ }\mu\text{m}$ PSG layer, deposited and annealed at 1000°C for one hour, served as the sacrificial layer. After PSG patterning, a $2\text{ }\mu\text{m}$ structural polysilicon layer was deposited under the same conditions listed above, except the deposition temperature for this layer was 585°C . These polysilicon deposition conditions, followed by an RTA anneal at 900°C after patterning, have been shown to produce low stress, low strain-gradient polysilicon films [23], which were necessary to obtain the long, *flat* beams (up to 1000 microns) used in this work.

In-use stiction was measured by determining the cantilever beam detachment length and calculating a work of adhesion for the contacting surfaces [3,16,24]. Testing in-use stiction with the cantilever beam arrays required actuation of the beams down into contact with the underlying ground-plane surface. A sticking probability, defined as the ratio of the number of beams stuck to the total number of beams actuated, was calculated for each beam length and surface treatment examined.

For hydrophilic surfaces, tested as a reference for this work, beam actuation was accomplished by pushing the beams down with a sharp probe tip, then releasing them. However, adhesion between the probe tip and the beam surface precluded probe-tip actuation for the hydrophobic SAM-coated structures. A second generation of structures was therefore designed and built which incorporated an electrostatic actuation pad, as shown in Fig. 2. By applying 150 V between the actuation pad and the beams/landing pad, the beams could be pulled into contact with the landing pad without making contact with the actuation pad. By utilizing a single actuation pad, an entire beam array could be tested at the same time; the beam arrays were typically pulled down and released several times before results were recorded. It was also

important to record the results immediately after testing, since transportation of the samples was observed to cause beams to become unstuck in some cases. Using a voltage of 150 V, beams as short as about 400 microns could be pulled into contact; higher voltages resulted in contact and shorting problems with the actuation pad.

Figure 2. Top view picture (a) and side view schematic (b) of electrostatically-actuated cantilever beam arrays. Polysilicon structures were built with a 3000 Å ground-plane layer and a 2 μm structural layer in a 3-mask process. After fabrication, individual die were annealed in argon for 5 minutes at 900-1000 °C to obtain low stress, low strain-gradient films.

Thermal stability experiments were carried out at atmospheric pressure by heating SAM films in an rapid thermal annealing system [AG Associates Heatpulse 210] to the specified temperature. For films annealed in nitrogen or oxygen, the sample chamber was purged for five minutes with 50 sccm of flowing gas. Vacuum experiments were conducted in a vacuum packaging station with a glass chamber pumped down to below 10^{-4} torr. Specified annealing temperatures were achieved with an IR lamp and were measured by a thermocouple mounted to the back of the sample holder. Contact angle measurements employed the Sessile drop method and used DI water (resistivity ≥ 18 MΩ) as the measurement liquid. Liquid drops were typically 4 μl, and the contact angle was measured with a goniometer [Ramé-Hart, Inc.].

SAM depositions were carried out using standard solvent-grade chemicals, except for hexadecane and iso-octane which were anhydrous grades (Aldrich Chemical Co.). The OTS was purchased from Aldrich at 95% purity, and was used as-received. The mixture used for SAM deposition was a ~1 mM OTS solution in 4:1 hexadecane:CCl₄ or hexadecane:CHCl₃ - about 1 drop (~20

μl) of OTS per 50 ml of solvent. The SAM deposition and the peroxide soak were 15 minutes, and rinse times were typically 10 minutes. All steps in the process consisted of dilution rinses in order to keep the structures from leaving the liquid phase. Rinses were accomplished either by simple dilutions or by moving structures from one solution to the next while entraining a liquid dome on the wafer surface. All glassware was dehydrated in a 90 °C oven prior to use, and reactions were carried out in a chemical fume hood.

RESULTS AND DISCUSSION

Release Stiction. The microstructure release process incorporating SAM films is given in Table 1. Once structures were freed in HF (diluted 5:1 with water), the polysilicon surfaces had to be reoxidized for the SAM formation to occur. This was accomplished by forming a chemical oxide with hydrogen peroxide. Before immersion in the OTS solution, the bulk water had to be removed from the samples. Hence, samples were rinsed with iso-propanol (IPA) then carbon tetrachloride (CCl₄) prior to entering the OTS mixture. After SAM formation, the excess precursor molecules were rinsed from the surface with CCl₄, and the CCl₄ was rinsed away with IPA. The release process up to this point was adapted from Alley *et al.* who used methanol instead of iso-propanol, and allowed the samples to dry under an IR lamp after the last solvent rinse [2].

A major concern regarding this work and its industrial application is the use of carbon tetrachloride in the SAM coating process. This is because CCl₄ was banned for most industrial uses under the Montreal Protocol. The role of CCl₄ in the SAM process is to help dehydrate the structures prior to film formation, help solvate the OTS head group in the solvent mixture, and to rinse away excess OTS molecules which may be physisorbed to the surface. Miscibility and wettability issues are also important in choosing a replacement solvent, since liquid must be entrained when moving from one solution to the next. Very recently we found that a combination of chloroform and iso-octane can also be used to produce high-quality SAM films without the use of CCl₄. In this process, iso-octane replaces CCl₄ for the rinses before and after SAM formation, and chloroform is substituted for the CCl₄ in the OTS mixture. Structures coated using these new solvents have shown equal or better performance compared to the films deposited using CCl₄, and the results reported in this work are applicable to both deposition techniques.

Table 1. Summary of the release and SAM-coating process for polysilicon microstructures. Numbers in parentheses indicate that that rinse was performed twice in succession. See text for details. **Note:** Failure to rinse away all of the excess OTS molecules between steps (iii) and (iv) will lead to residue and/or polymer formation on the structure surfaces! This problem is particularly prevalent if the OTS concentration is too high (>5 mM) during the SAM formation step.

i) Sacrificial Layer Etch	Dilute HF (5:1 v/v H ₂ O)
ii) Surface Oxidation	H ₂ O rinse, H ₂ O ₂ soak, H ₂ O rinse
iii) SAM Formation	IPA rinse (2), CCl ₄ rinse (2), OTS solution, CCl ₄ rinse (2)
iv) Rinse and Dry	IPA rinse (2), H ₂ O rinse, pull structures directly from water!

We have refined Alley's release process a step further by taking advantage of the extremely hydrophobic SAM-coated surfaces. At the end of the release process, instead of drying the structures from the IPA (or methanol) rinse, the IPA was instead displaced by water. The structures were then pulled directly out of the water, where they emerged released and completely dry. The structures required no further drying because water dewetted the SAM-coated surfaces immediately as the structures came out of the water. This release technique has been used to successfully release cantilever beam arrays containing beams up to 1 mm long, as pictured in Fig. 3. Other devices such as Sandia microengines [25] have also been coated and released successfully.

While many surfaces will dewet when pulled from water (e.g., an HF-treated silicon surface, contact angle $\approx 70^\circ$), it has been our experience that compliant, uncoated structures pulled from an HF or water solution in the same manner as described above will invariably emerge stuck to the substrate or to adjacent microstructure surfaces. We believe the success of the SAM treatment in this regard results from the water contact angle of $\sim 114^\circ$ present on these surfaces. Figure 4 shows a simplified picture of the water droplet shape and the corresponding meniscus shape for surfaces with contact angles above and below 90° . On the more hydrophilic surface, the meniscus shape will be concave underneath a compliant structure, creating a capillary force sufficiently strong to pull these surfaces into contact. Alternatively, on a SAM-coated structure, the water meniscus will maintain a convex curvature, thus giving rise to no attractive forces between the two surfaces.

The success of the release process outlined in Table 1 appears to depend on the extreme hydrophobicity (i.e. low surface energy) of the SAM-coated oxidized silicon surfaces. Since the dewetting of the microstructures is a dynamic process (i.e. not an equilibrium process), the receding contact angle will actually determine the meniscus shape during dewetting. Fortunately, there is little hysteresis in advancing and receding contact angles on high-quality SAM films [21], and receding contact angles remain $\sim 114^\circ$. Viscous forces due to water streaming will also act on the microstructures when they are pulled from the water rinse; however, these viscous forces have not led to significant stiction problems on the structures released to date.

Figure 3. Scanning electron micrograph of SAM-coated cantilever beams released using the process outlined in Table 1. Even the longest beam (1 mm) was successfully released without sublimation or supercritical drying techniques.

In-Use Stiction. After coating and releasing the cantilever beam arrays described above, these structures were then used to quantify the in-use stiction properties of SAM-coated devices. Upon electrostatically actuating the cantilever beams into contact with the underlying substrate, the status of each beam (stuck or unstuck) was recorded. The sticking probability data for three different microstructure surfaces is shown in Fig. 5, where the sticking probability is plotted as a function of beam length. For the H_2O_2 and NH_4F -treated structures [see Ref. 16], the sticking probability curves cross the 50% line at a beam length of approximately 110 and 680 microns, respectively. The sticking probability data for the SAM-coated surfaces is also shown in Fig. 5, and it can be seen that even at a beam length of 950 microns, only about half of the beams remain stuck upon making contact with the substrate.

Figure 4. Water contact angles and corresponding droplet shape on hydrophilic oxide (a) and hydrophobic SAM-coated (b) surfaces. Underneath the hydrophilic beam, the concave meniscus creates a capillary force which acts to bring the cantilever beam into contact with the substrate. No such attractive capillary force exists underneath the SAM-coated beam, however, where the meniscus maintains a convex curvature.

If the detachment length is taken as the length at which the sticking probability is equal to 50%, work of adhesion values can then be estimated using the equation [3]

$$W_s = \frac{3}{8} \frac{Et^3h^2}{l_d^4} \quad (1)$$

Here, E is the Young's modulus of polysilicon, t is the polysilicon thickness, h is the sacrificial layer thickness, and l_d is the detachment length. Using Eqn. (1), work of adhesion values for each of the treatments are calculated and shown in Table 2, which reveals a dramatic decrease in the work of adhesion on hydrophobic surfaces. Specifically, the SAM-coated structures exhibit a work of adhesion of $3 \mu J/m^2$, compared to $20,000 \mu J/m^2$ for structures with conventional hydrophilic surfaces. This corresponds to a reduction of nearly four orders of magnitude in work of adhesion.

The mechanism for stiction reduction is not yet completely understood. However, it seems likely that the adhesion phenomena are quite different in the case of the hydrophilic and hydrophobic surfaces. One would suspect that meniscus forces, driven by capillary condensation, are responsible for the relatively high adhesion seen on the hydrophilic samples. This suggestion is supported by the observation that under conditions of near 100% relative humidity, the detachment length for the hydrophilic surface decreases to about 65 microns, which translates to a work of adhesion of 140 mJ/m^2 - twice the surface tension of water [3,24].

Figure 5. Comparison of in-use stiction properties on hydrophilic, ammonium fluoride-treated, and SAM-coated surfaces. The structures used for all measurements were fabricated during the same processing run.

A contact angle greater than 90° , as seen on SAM-coated surfaces, prevents capillary condensation and the resulting meniscus force altogether. The attractive forces present in SAM-coated structures are therefore expected to originate from an entirely different adhesion mechanism. Adhesion energies on the hydrophobic surfaces appear to be on the order of van der Waals interactions, but surface roughness complicates a more quantitative calculation. Work is in progress to predict these adhesive forces based on the surface topology as measured by atomic force microscopy [24].

Thermal Stability. Figure 6 shows the water contact angles on polysilicon SAM-coated surfaces as a function of anneal temperature. These samples were annealed in either a nitrogen, oxygen, room air, or vacuum environment. For the samples annealed in nitrogen, the contact angles remained constant to 400°C , above which the contact angle began to decrease. Annealing experiments in vacuum were carried out to mimic an actual vacuum packaging process, and SAM films remained intact up to at least 400°C (the highest attainable temperature in our packaging system). Thus, it appears that the SAM thermal stability in vacuum or inert atmospheres is adequate for some packaging processes. To our knowledge, the thermal breakdown mechanism in the SAM films is not presently known. However, the film stability is much lower when annealed in oxygen or air, as shown in Fig. 6, indicating a mechanism for chemical reaction at elevated temperatures in oxygen-containing environments. These results appear to be consistent with literature reports of

film stability in inert atmospheres up to around 450°C [26] and film stability in air up to at least 140°C [27].

Table 2. Approximate detachment lengths and corresponding works of adhesion for each of the treatments listed in Fig. 5. Works of adhesion were calculated using Eqn. (1) with a polysilicon thickness, t , of $2.15 \mu\text{m}$, a sacrificial layer thickness, h , of $2.0 \mu\text{m}$, and a Young's modulus of 170 GPa .

Surface Treatment		Detachment Length (μm)	Work of Adhesion ($\mu\text{J/m}^2$)
H_2O_2	hydrophilic	110	20,000
NH_4F	hydrophobic	700	10
SAMs	hydrophobic	950	3

CONCLUSIONS AND FUTURE DIRECTIONS

This work has systematically investigated the anti-stiction properties of OTS self-assembled monolayer films. By converting the high surface-energy, hydrophilic silicon dioxide surface into a low surface-energy, hydrophobic surface, these films appear to avoid attractive meniscus forces. Not only does this alleviate stiction during the release process, it also eliminates capillary condensation, a dominant cause of in-use stiction. Both release-related and in-use stiction are reduced by almost four orders of magnitude in microstructures incorporating the SAM deposition and release process presented here. SAM films thus represent an anti-stiction surface passivation capable of surviving the packaging temperature cycle. These results, coupled with the well-documented long-term stability of SAM films in various ambients, suggest great promise for use of these films as anti-stiction coatings in micromechanical devices.

Figure 6. Thermal stability of SAM films on polysilicon in typical packaging environments. Samples were heated to the specified annealing temperature for 5 minutes, then allowed to cool to below 100°C before removal and measurement.

Self-assembled monolayers also have the advantageous characteristic that the tail group of the precursor molecules can be varied a great deal. For instance, tail lengths for most types of films can be changed to produce thicker or thinner films, and SAM layers might be formed directly on the silicon surface,

eliminating the need for an underlying oxide layer [28]. Other possibilities include changing the deposition method used to form SAMs, possibly by employing a vapor-phase deposition process, which has been demonstrated for some types of films [29]. Finally, recent work involving fluorinated trichlorosilane (FTS) molecules has produced films which exhibit surface energies three times lower than those obtained with the best OTS films [22]. The wide range of options available in investigating and choosing a suitable SAM film makes this a potentially versatile anti-stiction technology.

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References

1. H. Guckel, J.J. Sniegowski, T.R. Christenson, and F. Raissi, *Sensors and Actuators*, **A21**, 346 (1990).
2. R.L. Alley, R.T. Howe, and K. Komvopoulos, *Proc. IEEE Solid-State Sensor and Actuator Workshop*, Hilton Head, SC, USA, June 21-24, 1992, p. 202.
3. C.H. Mastrangelo and C.H. Hsu, *Proc. IEEE Solid-State Sensor and Actuator Workshop*, Hilton Head, SC, USA, June 21-24, 1992, p. 208.
4. N. Takeshima, K.J. Gabriel, M. Ozaki, J. Takahashi, H. Horiguchi, and H. Fujita, *Transducers '91*, San Francisco, CA, USA, June 24-27, 1991, p. 63.
5. G.T. Mulhern, D.S. Soane, and R.T. Howe, *Transducers '93*, Yokohama, Japan, June 7-10, 1993, p. 296.
6. T.A. Core and R.T. Howe, "Method for fabricating microstructures," US Patent # 5,314,572, May 24, 1994.
7. C.H. Mastrangelo and G.S. Saloka, *Proc. IEEE MEMS Workshop*, Ft. Lauderdale, FL, USA, Feb. 7-10, 1993, p. 77.
8. T. Abe, W.C. Messner, and M.L. Reed, *Proc. IEEE MEMS Workshop*, Amsterdam, the Netherlands, Jan. 29 - Feb. 2, 1995, p. 94.
9. W.A. Clark, R.T. Howe, and R. Horowitz, this conference (Hilton Head '96).
10. T. Juneau and A.P. Pisano, this conference (Hilton Head '96).
11. L.-S. Fan, Y.-C. Tai, and R.S. Muller, *IEEE Int. Electr. Dev. Meet.*, San Francisco, CA, USA, Dec. 11-14, 1988, p. 666.
12. W.C. Tang, T.-C. H. Nguyen, and R.T. Howe, *Proc. IEEE MEMS Workshop*, Salt Lake City, UT, USA, Feb. 20-22, 1989, p. 53.
13. R.L. Alley, P. Mai, K. Komvopoulos, and R.T. Howe, *Transducers '93*, Yokohama, Japan, June 7-10, 1993, p. 288.
14. Y. Yee, K. Chun, and J.D. Lee, *Transducers '95*, Stockholm, Sweden, June 25-29, 1995, p. 206.
15. K. Deng, R.J. Collins, M. Mehregany, and C.N. Sukkenik, *Proc. IEEE MEMS Workshop*, Amsterdam, the Netherlands, Jan. 29 - Feb. 2, 1995, p. 368.
16. M.R. Houston, R. Maboudian, and R.T. Howe, *Transducers '95*, Stockholm, Sweden, June 25-29, 1995, p. 210.
17. M.R. Houston and R. Maboudian, *J. Appl. Phys.*, **78**, 3801 (1995).
18. P.F. Man, B.P. Gogoi, and C.H. Mastrangelo, *Proc. IEEE MEMS Workshop*, San Diego, CA, USA, Feb. 11-15, 1996, p. 55.
19. S.R. Wasserman, Y.-T. Tao, and G. Whitesides, *Langmuir*, **5**, 1074 (1989).
20. A. Ulman, *Introduction to Ultra-thin Organic Films: From Langmuir Blodgett to Self-Assembly*, Academic Press, San Diego, CA, 1991.
21. A.N. Parikh, D.L. Allara, I.B. Azouz, and F. Rondelez, *J. Phys. Chem.*, **98**, 7577 (1994).
22. J.B. Brzoska, I.B. Azouz, and F. Rondelez, *Langmuir*, **10**, 4367 (1994).
23. M. Biebl, G.T. Mulhern, and R.T. Howe, *Transducers '95*, Stockholm, Sweden, June 25-29, 1995, p. 198.
24. M.R. Houston, R. Maboudian, and R.T. Howe, manuscript in preparation.
25. E.J. Garcia and J.J. Sniegowski, *Sensors and Actuators*, **A48**, 203 (1995).
26. P. Fountaine, D. Goguenheim, D. Deresmes, D. Vuillaume, M. Garet, and F. Rondelez, *Appl. Phys. Lett.*, **62**, 2256 (1993).
27. S.R. Cohen, R. Naaman, and J. Sagiv, *J. Phys. Chem.*, **90**, 3054 (1986).
28. M.R. Linford, P. Fenter, P.M. Eisenberger, and C.E.D. Chidsey, *J. Am. Chem. Soc.*, **117**, 3145 (1995).
29. R.M. Wallace, P.J. Chen, S.A. Henck, and D.A. Webb, *J. Vac. Sci. Technol. A*, **13**, 1345 (1995).